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Flight Operations Simulation and Analysis Branch
Flight Technologies and Procedures Division
Flight Standards Service

Safety Study Report for Terminal Radar Separation Passing or Diverging Standards Applied to En route Display Systems Using ASR-9 and ARSR Radars

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12. Abstract

Radar separation standards for control of aircraft within the United States National Airspace System (NAS) are given in Section 5 of FAA Order 7110.65, Air Traffic Control (ATC). As this order states, aircraft may be separated in various ways depending upon such factors as type of radar system used, distance of the aircraft from the radar system antenna, terminal or en route ATC environment and vertical distance. If vertical separation can not be assured, terminal controllers can use the following separation methods:
1) lateral separation by 3 NM when the aircraft is within 40 miles of the radar antenna and Broadband/Full Digital Terminal Radar System is used and 2) aircraft are passing or diverging and one aircraft has crossed the projected course of the other and the angular difference between their courses is at least 15 degrees. Boston Air Route Traffic Control Center (ARTCC) has proposed that the two terminal separation methods described above be applied to the en route ATC environment. This request is in light of the fact that radar data from the same digital radar system used in the terminal environment, the Airport Surveillance Radar (ASR)-9, is available to en route ARTCC's. This report presents the results of a study which compared the performance of the ASR-9 and the Air Route Surveillance Radar (ARSR) radar systems when used in an ARTCC environment to a baseline system of an ASR-9 used in a Terminal Radar Approach Control (TRACON) environment. The study objective was to determine the adjustment (if any) in the application of in-trail lateral separation and course divergence standards applied to en route surveillance systems such that actual aircraft to aircraft separation is not less than that achieved using terminal systems.

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Executive Summary

Radar separation standards for control of aircraft within the United States National Airspace System (NAS) are given in Section 5 of FAA Order 7110.65, Air Traffic Control (ATC). As this order states, aircraft may be separated in various ways depending upon such factors as type of radar system used, distance of the aircraft from the radar system antenna, terminal or en route ATC environment and vertical distance. If vertical separation can not be assured, terminal controllers have the following separation methods at their disposal: 1) lateral separation by 3 NM when the aircraft is within 40 miles of the radar antenna and Broadband/Full Digital Terminal Radar System is used and 2) aircraft are passing or diverging and one aircraft has crossed the projected course of the other and the angular difference between their courses is at least 15 degrees.

Boston Air Route Traffic Control Center (ARTCC), better known as Boston Center and abbreviated ZBW, has proposed that the two terminal separation methods described above be applied to the en route ATC environment. ZBW's request is in light of the fact that radar data from the same digital radar system used in the terminal environment, the Airport Surveillance Radar (ASR)-9, is available to en route ARTCCs. This report presents the results of a study that compared the performance of the ASR-9 and the Air Route Surveillance Radar (ARSR) radar systems when used in an ARTCC environment adapted for single sensor to a baseline system of an ASR-9 used in a Terminal Radar Approach Control (TRACON) environment. The ARTCC environment defined for this study is the Host Computer System (HCS) and Display System Replacement (DSR). Given the differing antenna scan rates of the ASR-9 and the ARSR and the differing latency times of the ARTCC and TRACON processing/display systems, the study objective was to determine the adjustment (if any) in the application of in-trail lateral separation and course divergence standards for en route surveillance systems such that actual aircraft to aircraft separation is not less than that achieved using terminal systems.

Based on study results, the following conclusions can be drawn concerning in-trail separation standards:

a. when using ASR-9 radar data in the ARTCC HCS/DSR processing/display system, no adjustment is necessary in the application of separation minima.

b. when using ARSR radar data in the ARTCC HCS/DSR processing/display system and closure speeds exceed approximately 120 Knots the following adjustments to the application of in-trail separation adjustments as shown in the table below should be made.

In-trail Separation Application Adjustments Using ARSR

Closure Speed (Knots)	In-trail Separation Application Adjustment (NM)
120	+0.5
150	+0.6
180	+0.75
210	+0.9
240	+1.0
270	+1.15
300	+1.25

Based on study results, the following conclusions can be drawn concerning course divergence separation standards:

a. when using ASR-9 radar data in the ARTCC HCS/DSR processing/display system modified to write at 6-second intervals, relatively small course divergence angular adjustments are necessary. These adjustments range from 1.78° at 200 Knots groundspeed to 0.86° at 400 Knots groundspeed.

b. when using ARSR radar data in the ARTCC HCS/DSR processing/display system a course divergence angular adjustment is necessary. This adjustment ranges from 28.52° for an aircraft at 200 Knots groundspeed to 13.89° for an aircraft at 400 Knots groundspeed. Thus for either aircraft at 200 Knots groundspeed in a course divergence separation scenario, a course divergence angle of 43.52° (original 15° + 28.52° adjustment) would have to be observed and maintained for vertical separation to be discontinued.

c. since this study does not address radar system position errors caused by system plane projections between aircraft broadcasting mode C information and non-mode C aircraft, the course divergence procedures can only be applied between validated mode C aircraft or non-mode C aircraft that have the altitude entered by the controller.

d. altitude limitation for this study is bounded by the slant range distance of 40 NM for non-mode C aircraft. Basic altitude restrictions are those of each individual sensor or 41,000 ft Mean Sea Level (MSL) whichever is greater.

Table of Contents

List of Tables

List of Figures

Safety Study Report for Terminal Radar Separation Passing or Diverging Standards Applied to En route Display Systems Using ASR-9 and ARSR Radars

1.0. Introduction

Radar separation standards for control of aircraft within the United States National Airspace System (NAS) are given in Section 5 of FAA Order 7110.65, Air Traffic Control (ATC) (Reference 1). As Reference 1 states, aircraft may be separated in various ways depending upon such factors as type of radar system used, distance of the aircraft from the radar system antenna, terminal or en route ATC environment and vertical distance. If vertical separation can not be assured, terminal controllers have the following separation methods at their disposal: 1) lateral separation by 3 NM when the aircraft is within 40 miles of the radar antenna and Broadband/Full Digital Terminal Radar System is used and 2) aircraft are passing or diverging and one aircraft has crossed the projected course of the other and the angular difference between their courses is at least 15 degrees.

Boston Air Route Traffic Control Center (ARTCC), better known as Boston Center and abbreviated ZBW, has proposed that the two terminal separation methods described above be applied to the en route ATC environment. ZBW's request is in light of the fact that radar data from the same digital radar system used in the terminal environment, the Airport Surveillance Radar (ASR)-9, is available to en route ARTCCs. This report presents the results of a study which compared the performance of the ASR-9 and the Air Route Surveillance Radar (ARSR) radar systems when used in an ARTCC environment adapted for single sensor to a baseline system of an ASR-9 used in a Terminal Radar Approach Control (TRACON) environment. The ARTCC environment defined for this study is the Host Computer System (HCS) and Display System Replacement (DSR). Given the differing antenna scan rates of the ASR-9 and the ARSR and the differing latency times of the ARTCC and TRACON processing/display systems, the study objective was to determine the adjustment (if any) in the application of in-trail lateral separation and course divergence standards for en route surveillance systems such that actual aircraft to aircraft separation is not less than that achieved using terminal systems.

2.0. Description of the Model

2.1. The Surveillance Systems

As previously stated two radar systems, ASR-9 and ARSR, were paired with the ARTCC HCS/Display System Replacement (DSR) processing/display system adapted for single sensor and subsequently compared against a baseline of an ASR-9 with TRACON processing/display system. The ASR-9 is a modern, digital radar procured primarily for terminal airport surveillance. The ARSR is used primarily as a long-range en route surveillance system.

For purposes of this report, the ASR-9/TRACON baseline will be referred to simply as Baseline, while the ASR-9/ARTCC combination will be referred to as ZBW-ASR9 and, lastly, the ARSR/ARTCC combination will be referred to as ZBW-ARSR

Table 1 shows parameters of interest for each of the three surveillance systems. Table 1 values are taken from an undated compilation of surveillance sensor performance specifications (Reference 2).

System	Site Sensor	Communication	Reserve	Automation & Display	Total Latency
Baseline	.8	.3	.1	1.0	2.2
ZBW-ASR9	.8	.3	.1	1.6	2.8
ZBW-ARSR	1.5	.3	.1	1.6	3.5

Table 1: Surveillance System Latency Parameters (Seconds)

Site sensor is the delay encountered at the radar site itself, communication is the delay encountered in sending the radar data from the radar site to the TRACON or ARTCC, a reserve of .1 second is built-in, and the automation and display latency accounts for the delay in processing and displaying the radar data to the controller.

In addition to surveillance system latency values, scan rates of the respective radar systems are also of importance to this study. Table 2 shows the ASR-9 and ARSR scan rates.

ASR-9	12.5 rpm (4.8 sec. per scan)
ARSR	5 rpm (12 sec. per scan)

Table 2: Radar System Scan Rates

Another and perhaps the most critical parameter associated with the study is the DSR display rate. After radar target data has been processed, it is sent to buffers for display by the DSR. The DSR display rate is the time required for display of all currently buffered radar target data. Table 3 shows the DSR display rates used for the three systems of interest. While the display rates shown for the baseline and ZBW-ARSR systems are based on system performance specifications, the display rate for the ZBW-ASR9 is an assumption based on discussions with personnel at ZBW.

Baseline	4.8
ZBW-ASR9	6
ZBW-ARSR	12

Table 3: DSR Display Rates (Seconds)

(Note: It must be emphasized that the results reported in this study are heavily dependent upon the DSR display rates as shown in Table 3. In particular, there is some question as to whether the ZBW-ASR9 system can achieve a 6 second DSR display rate. If this is the

case, the results presented in this report for the ZBW-ASR9 would be closer to those reported for the ZBW-ARSR.)

2.2. Airspace Simulation and Analysis Tool (ASAT)

The primary analysis tool for this safety evaluation was ASAT. ASAT is a multifaceted, highly adaptable computer-based tool for aviation related simulations and safety evaluations. ASAT consists of high fidelity models and in some cases, empirical data representing the following major components of a typical real world operational aviation scenario:

a. At the heart of the system is high fidelity engineering flight dynamics models of actual aircraft obtained through various government/industry partnerships. Model definition and performance is also enhanced and tailored by empirical data collected in flight simulators and flight tests. Aircraft avionics are modeled based on requirements of the particular scenario. ASAT can model a broad range of advanced navigation systems such as Flight Management System (FMS), Global Positioning System (GPS), and Required Navigation Performance (RNP) as well as older navigation systems such as Instrument Landing System (ILS), Microwave Landing System (MLS), and Distance Measuring Equipment (DME).

b. ASAT has access to a wide range of environmental models including temperature, atmospheric pressure, and wind profiles, both lateral and vertical. The aerodynamic flight models described above respond to the ASAT generated atmosphere around them in the same manner as actual aircraft do. In addition, ASAT contains an advanced aircraft wake vortex model which can generate and track wake vortices and identify encounters between wake vortices and scenario "aircraft."

c. The environment in which ASAT scenarios are run is further defined by official FAA databases providing precise geographic locations of airports, runways, navaids, routes, fixes, waypoints, and other facilities, such as radar site locations. In addition, ASAT incorporates the FAA's obstacle and terrain database for use in obstacle clearance studies.

d. Air traffic equipment impacts on scenarios are based on computer models of radar systems using manufacturer and government provided specifications. When and where necessary, the human factors contribution of air traffic controllers is measured during simulations and from this data, statistical distributions of controller response times can be determined and made available to ASAT.

For this study, ASAT was modified to allow control of the various parameters bearing on the study. This modified ASAT is called the Air Traffic Procedures Evaluator (ATPE). In particular, ASAT was modified to model the difference in scan rates, data latency times, and display rates of the three surveillance systems. These parameters are critical in determining how the air traffic control situation has changed from the time the aircraft is detected by the radar to the time this information is displayed to a controller. ATPE can also handle aircraft at various speeds and turn rates.

2.3. In-trail Separation Model

The in-trail operational scenario consists of two aircraft flying along the same track in the same direction. The lead aircraft advances at a ground speed of V_{Lead} and the trailing aircraft at a ground speed of V_{Trail}. The ground speed of the trailing aircraft is greater than that of the leading aircraft ($V_{Trail} > V_{Lead}$) therefore, the in-trail separation is being reduced as time progresses.

In the ATPE model, both aircraft are being scanned by the selected radar system (see Figure 1). The radar data information is processed and the targets are displayed to the controller. Since the surveillance and monitoring systems are realistically modeled and the position of both aircraft was measured some time prior to the targets being displayed, the position of the aircraft as presented to the controller is not the same as the actual position of the aircraft at the time the data is being displayed. In broad terms, due to the scanning rate of the sensor and the latencies in the system, the controller's display will show the aircraft positions when the radar return was initially received at the antenna and not where the aircraft are when the data are being displayed. This situation is the essence of the in-trail operational scenario and is shown in Figure 2.

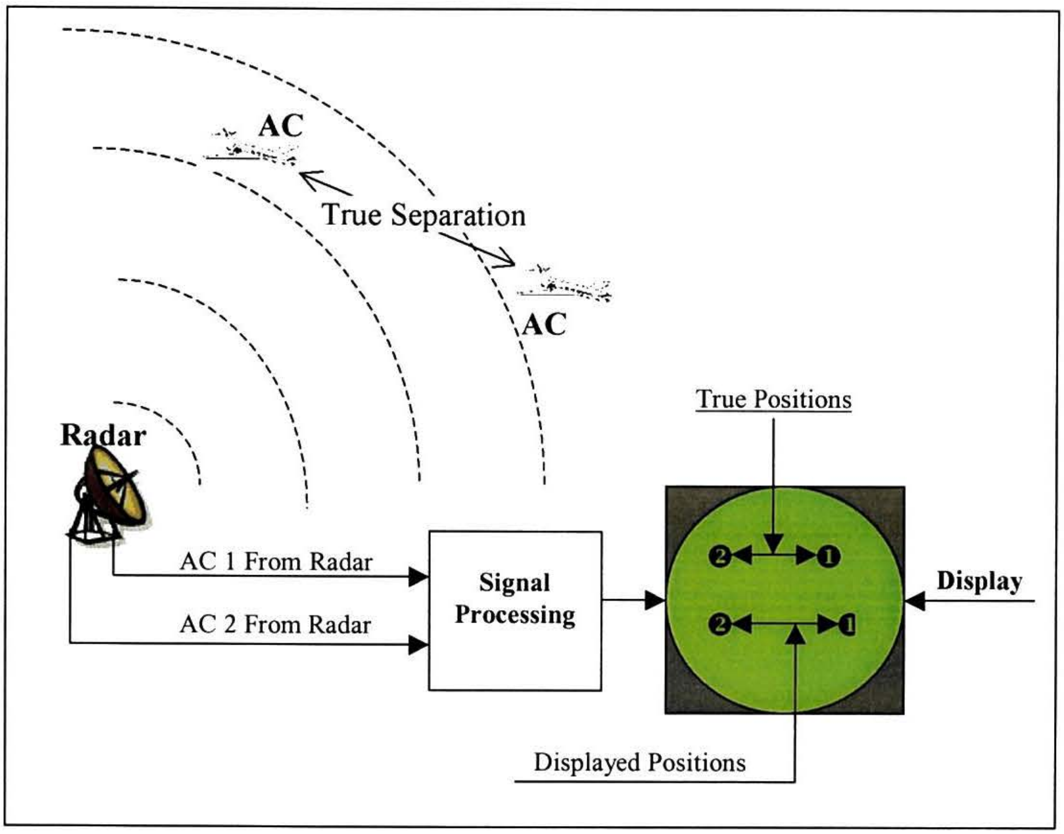

Figure 1: Depiction of In-trail Model

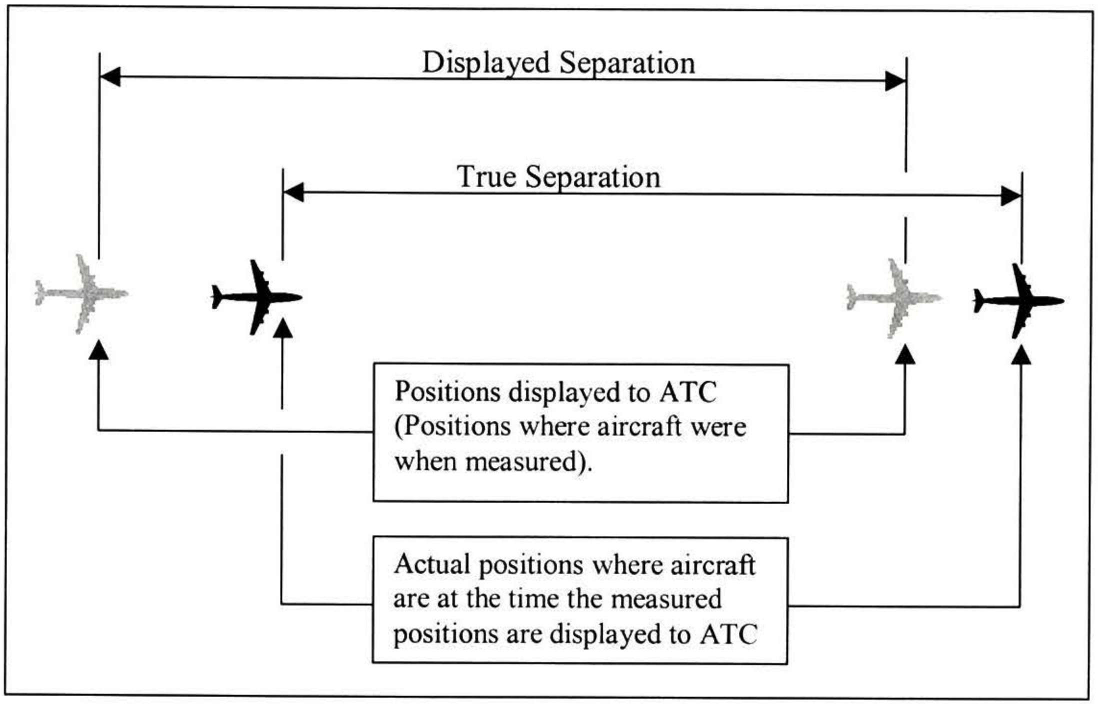

Figure 2: Depiction of In-trail Operational Scenario

The in-trail operational scenario ATPE model is further explained below:

- Initial Positions:
  - The leading aircraft is initialized at a given North/East distance from the sensor at a ground track of 090 degrees.
  - The trailing aircraft is initialized at a distance of 5.0 NM behind the leading aircraft on the same track.
- Speeds:
  - The leading aircraft is initialized at a ground speed of approximately 150 Knots.
  - The trailing aircraft is initialized at a ground speed of either 300 Knots or 450 Knots resulting in closure speeds of 150 Knots or 300 Knots, respectively.
- Surveillance Systems:
  - One of the surveillance systems under study is selected with its attendant scan rate, latency times, and display rates.
- Test Criterion:
  - The simulated controller first recognizes that the 3.0 NM separation standard is compromised.
- Sequence of Events:
  - The simulation starts with the trailing aircraft approaching the leading aircraft. The surveillance and monitoring system measures the position of both aircraft, processes the information, and displays the processed information to the simulated controller.

- Once the simulated controller identifies aircraft are at the selected criteria distance of 3.0 NM or less, the actual distance between aircraft is logged and that simulation run is completed. A total of 10,000 ASAT runs were accomplished for each surveillance system/closure speed combination.

For each surveillance system/closure speed combination, 10,000 ATPE runs were conducted and statistically analyzed. This analysis was used to determine the characteristics of the statistical function that describes the actual in-trail distance between aircraft at the time the controller identified that the 3 NM test criterion had been compromised. A mean (μ) and standard deviation (σ) was calculated for each surveillance system and closure speed combination. The ASR-9/TRACON surveillance system with the various closure speeds served as the baseline against which the other systems were compared.

Figure 3 shows an ATPE screen for modeling an in-trail separation scenario. The various parameters of interest, which have been discussed previously can be selected and changed using the windows on the left side of the display and the actual output of a single ATPE run is displayed on the right side.

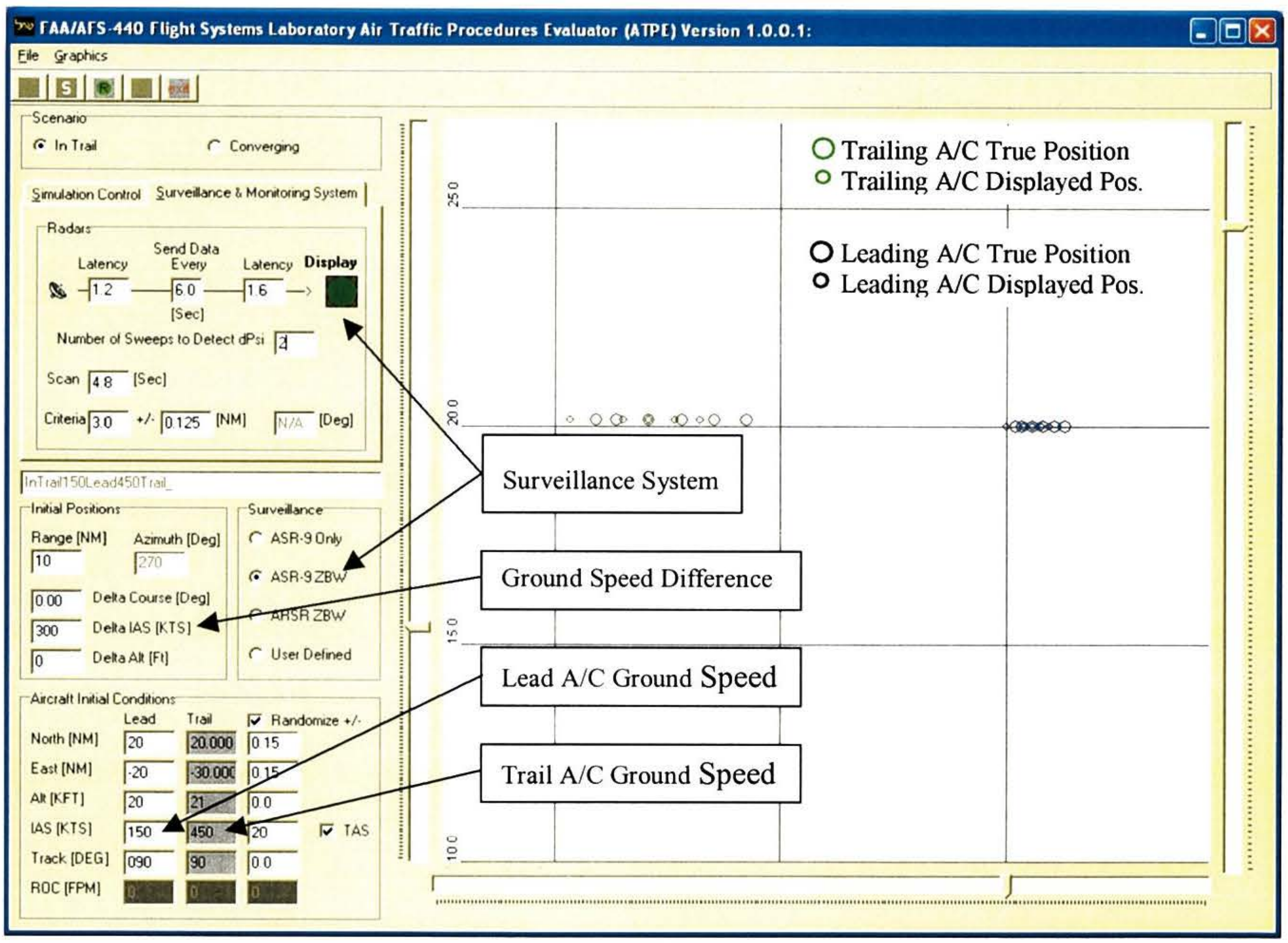

Figure 3: ATPE In-trail Model Screen

2.4. Course Divergence Model

(Note: For purposes of this report, the terms "course" and "track" are used interchangeably.)

Current terminal area ATC rules require a minimum of 15° course divergence between the projected track of an aircraft crossed by a second aircraft in order to discontinue vertical separation between the two aircraft. Since the controller's decision to discontinue vertical separation is based primarily upon the angle between aircraft tracks as displayed on the controller's monitor, the criteria used in the analysis of this operational scenario will be based upon the manner in which a change in ground track can be identified by a controller. Therefore, unlike the in-trail operational scenario, the diverging tracks operational scenario consists of a single aircraft executing a turn, as shown in Figure 4.

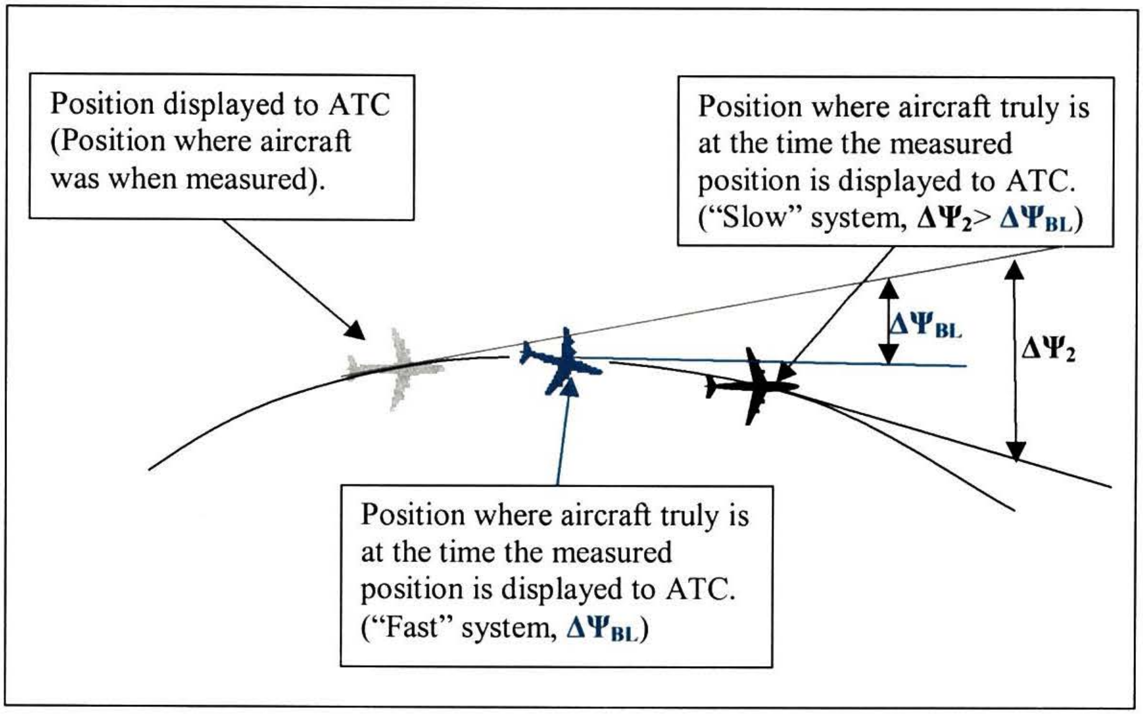

Figure 4: Graphic Depiction of Course Divergence Scenario

The course divergence scenario is modeled as follows:

- Initial Position:
  - The aircraft is initialized at a given North/East distance from the sensor at a ground track of 075 degrees.
- Speeds:
  - The aircraft is initialized at a ground speed of either 200 Knots or 400 Knots
- Surveillance Systems:
  - One of the surveillance systems under study is selected with its attendant scan rate, latency times, and display rate.

- Test Criterion:
  - Turn of 15° as identified by ATC. *Even though a 15° value was selected, any other value could be selected as long as it is large enough that it will ensure that the turning aircraft has reached a stabilized turn rate and not be in the phase of rolling into the turn bank angle.*
- Sequence of Events:
  - The simulation starts with the aircraft rolling into a nominal bank angle of 20,° at a nominal roll (bank) rate of 4.0°/second.
  - The simulated surveillance and monitoring system measures the position of the aircraft, processes the information, and displays the processed information to the simulated controller.
  - Once the simulated controller identifies a change in ground track of at least 15,° the actual track of the aircraft is logged and that simulation run is terminated.

The purpose of the diverging course operational scenario was to determine the difference between the actual course of the aircraft and the displayed course at the time the controller identifies the desired change in course (in this case 15°) has occurred. This difference in course using the baseline surveillance system will be called Delta Course Base Line or $\Delta\Psi_{BL}$. This scenario was performed twice for a nominal ground speed of 200 Knots and 400 Knots.

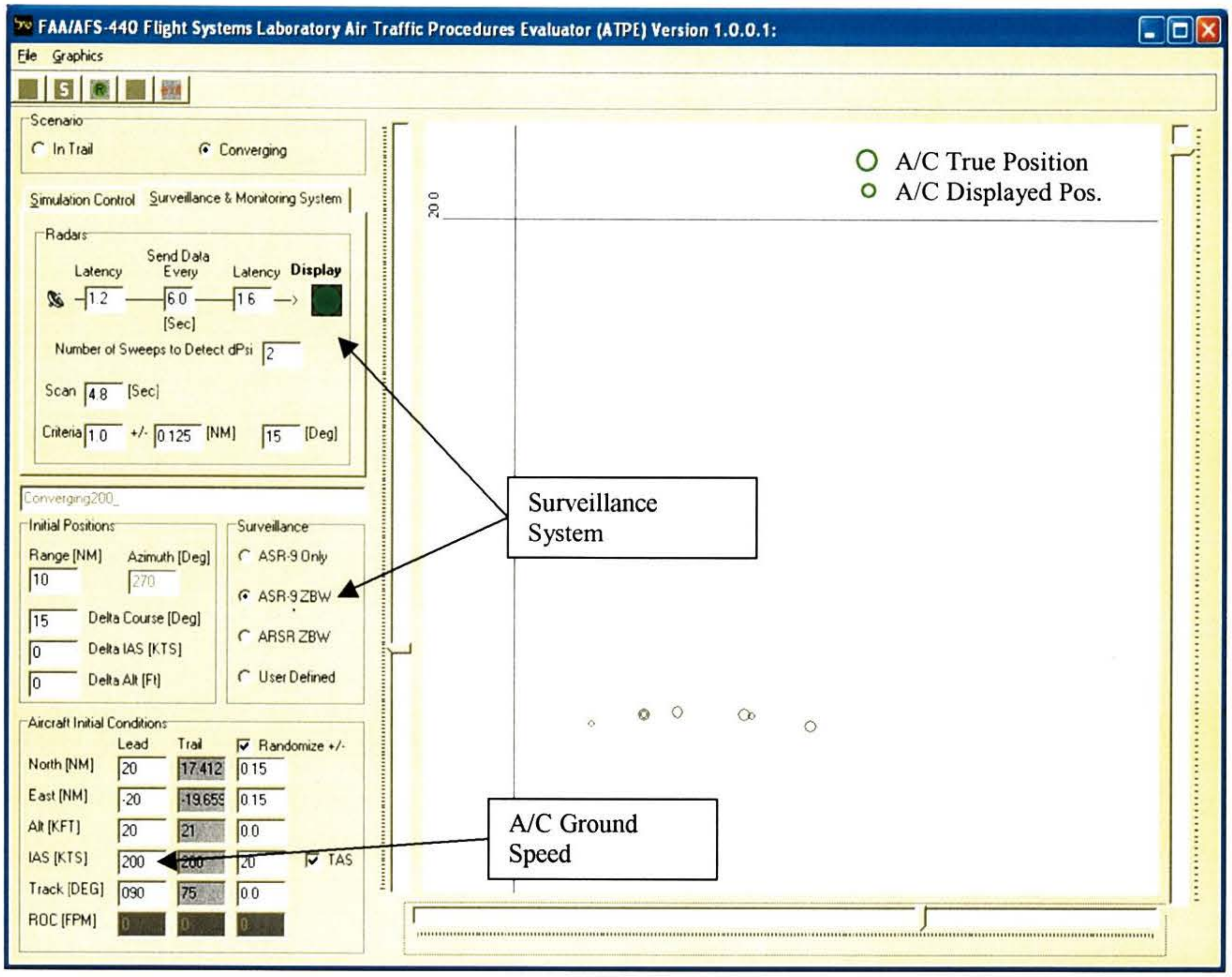

Figure 5: ATPE Course Divergence Model Screen

Next, the same operational scenarios were evaluated using the other surveillance systems, i.e., ZBW-ASR9 and ZBW-ARSR. Since critical parameters of the system such as scanning rates, latency times, and display rates are different, a new Delta Course (Delta Course 2 or $\Delta\Psi_2$) value was measured for each surveillance system and ground speed combination. The assumption underlying the course divergence scenario is that the controller's action is driven by the displayed course difference between the two aircraft. Therefore, in order to ensure that the controller takes action when the two aircraft are in the same relative positions as in the baseline case, the difference between $\Delta\Psi_{BL}$ and $\Delta\Psi_2$ (or $\Delta\Psi$) is the amount in degrees which must be added to the baseline course divergence value of 15° to determine the course divergence separation standard for the ZBW-ASR9 and ZBW-ARSR systems. Figure 5 shows the ATPE screen used to model the course divergence scenario.

In order to apply a rule or standard, in this case the 15° course divergence to discontinue vertical separation standard, a controller must be able to recognize when conditions for application of that rule are no longer present. Thus the course divergence scenario was designed to account for the situation where an aircraft has been established on the proper course for application of the 15° course divergence standard, but makes an unexpected course change reducing the course divergence angle. The scenario determines for the various surveillance systems, the additional angular course divergence needed for controllers using slower surveillance systems to recognize that the course divergence standard has been compromised and should no longer be applied.

2.5. Controller Recognition Model

Results in both the in-trail and course divergence scenarios were dependent upon a "controller" recognizing some event, e.g., achievement or loss of 3 NM in-trail separation of 15° course divergence. Since this study did not include actual air traffic controllers, a suitable controller recognition model was needed. The controller recognition model used in this study was based on Reference 3. Reference 3 suggests that controllers are unlikely to recognize and act upon a deviation or occurrence of an event during the first presentation (commonly called a "hit") on a radar display. Rather Reference 3 states that it would take at least two hits before a controller would recognize a deviation or occurrence of an event. Therefore, for purposes of this study, a given event, e.g., achievement or loss of 3 NM in-trail separation of 15° course divergence, is considered to have been recognized by a controller on the second hit or radar system display presentation containing that information.

(Note: Reference 3 also makes the point that due to the time involved in recognizing a deviation, air traffic controllers do not typically allow aircraft to operate right at separation limits. Notwithstanding, the two hit controller recognition threshold adopted for this study, nothing in this report is meant to imply that controllers would allow separation standards to be compromised before taking action.)

3.0. Summary of Data Analysis

3.1. In-trail Separation Data Analysis

Table 4 shows the various in-trail operational scenarios with associated test parameters modeled during the course of this study. As stated previously, 10,000 ATPE runs were conducted for each scenario in Table 4.

The statistical analysis of those runs for closure speeds of 150 Knots, i.e., scenarios 1, 3, and 5, are shown in Table 5. Figure 6 shows histogram plots of the ATPE runs for each of the surveillance systems at closure speed of 150 Knots. Figure 6 depicts plots of the actual distance between aircraft at the time the controller recognized that the 3 NM in-trail separation standard was breached. As Figure 6 shows, very little difference was seen between the surveillance systems using the ASR-9, namely the baseline and ZBW-ASR9. However, a substantial difference in displayed separation versus actual separation exists between the ASR-9 systems and the ARSR system. This can be primarily attributed to the lower scan rate of the ARSR and the decreased display rate of the ZBW-ARSR system.

Scenario Number	Ground Speed [Knots]		System	Termination Condition [NM]
	Trailing A/C	Leading A/C		
1	300 ± 20	150 ± 20	Baseline	3.0 ± 0.125
2	450 ± 20			
3	300 ± 20		ZBW-ASR9	
4	450 ± 20			
5	300 ± 20		ZBW-ARSR	
6	450 ± 20			

Table 4: In-trail Separation Scenarios with Test Parameters

Value	Scenario #1	Scenario #3	Scenario #5
Mean	2.601366	2.576849	2.129086
Standard Error	0.001196	0.001285	0.002013
Median	2.603938	2.581099	2.13644
Standard Deviation	0.119618	0.128454	0.201305
Sample Variance	0.014309	0.0165	0.040524
Kurtosis	-0.29751	-0.31401	-0.34413
Skewness	-0.11416	-0.13574	-0.19489
Range	0.755021	0.822816	1.236792
Minimum	2.182881	2.124929	1.445458
Maximum	2.937902	2.947745	2.68225
Sum	26013.66	25768.49	21290.86
Count	10000	10000	10000
Confidence Level (95.0%)	0.002345	0.002518	0.003946

Table 5: In-trail Separation Scenarios Statistical Analysis (Closure Speed 150 Knots)

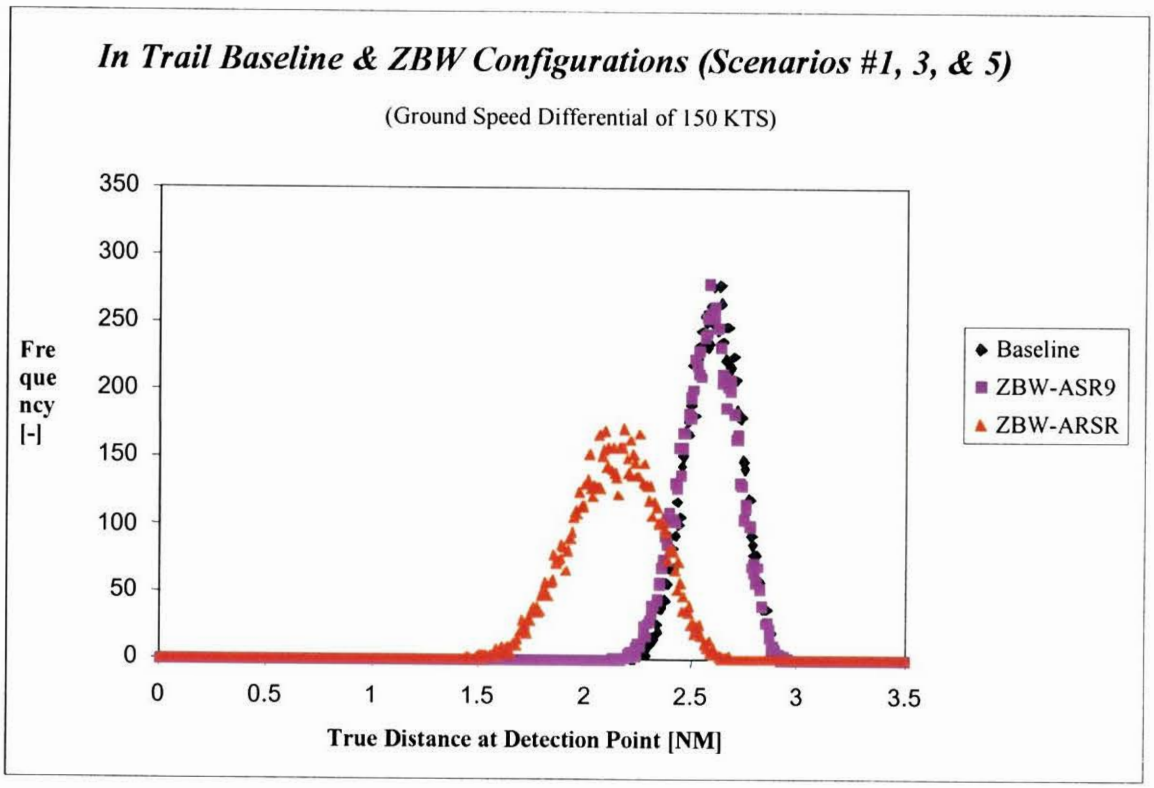

Figure 6: Histogram Plots of Actual In-trail Distances for Scenarios 1, 3, and 5

The statistical analysis of those runs for closure speeds of 300 Knots, i.e., scenarios 2, 4, and 6, are shown in Table 6. Figure 7 shows histogram plots of the ATPE runs for each of the surveillance systems at this closure speed. Figure 7 depicts plots of the actual distance between aircraft at the time the controller recognized that the 3 NM in-trail separation standard was breached. As was seen at 150 Knots, Figure 7 shows that at 300 Knots closure speed very little difference was seen between the surveillance systems using the ASR-9, namely the baseline and ZBW-ASR9. However, a substantial difference in displayed separation versus actual separation exists between the ASR-9 systems and the ARSR system. Again, this can be primarily attributed to the lower scan rate of the ARSR and the decreased display rate of the ZBW-ARSR system.

Value	Scenario #2	Scenario #4	Scenario #6
Mean	2.202357	2.153935	1.254814
Standard Error	0.001861	0.002068	0.003441
Median	2.206433	2.153167	1.258904
Standard Deviation	0.186092	0.206772	0.344085
Sample Variance	0.03463	0.042755	0.118395
Kurtosis	-0.39344	-0.42737	-0.61508
Skewness	-0.08725	-0.06762	-0.04709
Range	1.109909	1.219081	1.898978
Minimum	1.601179	1.505726	0.251939
Maximum	2.711088	2.724806	2.150917
Sum	22023.57	21539.35	12548.14
Count	10000	10000	10000
Confidence Level (95.0%)	0.003648	0.004053	0.006745

Table 6: In-trail Separation Scenarios Statistical Analysis
(Closure Speed 300 Knots)

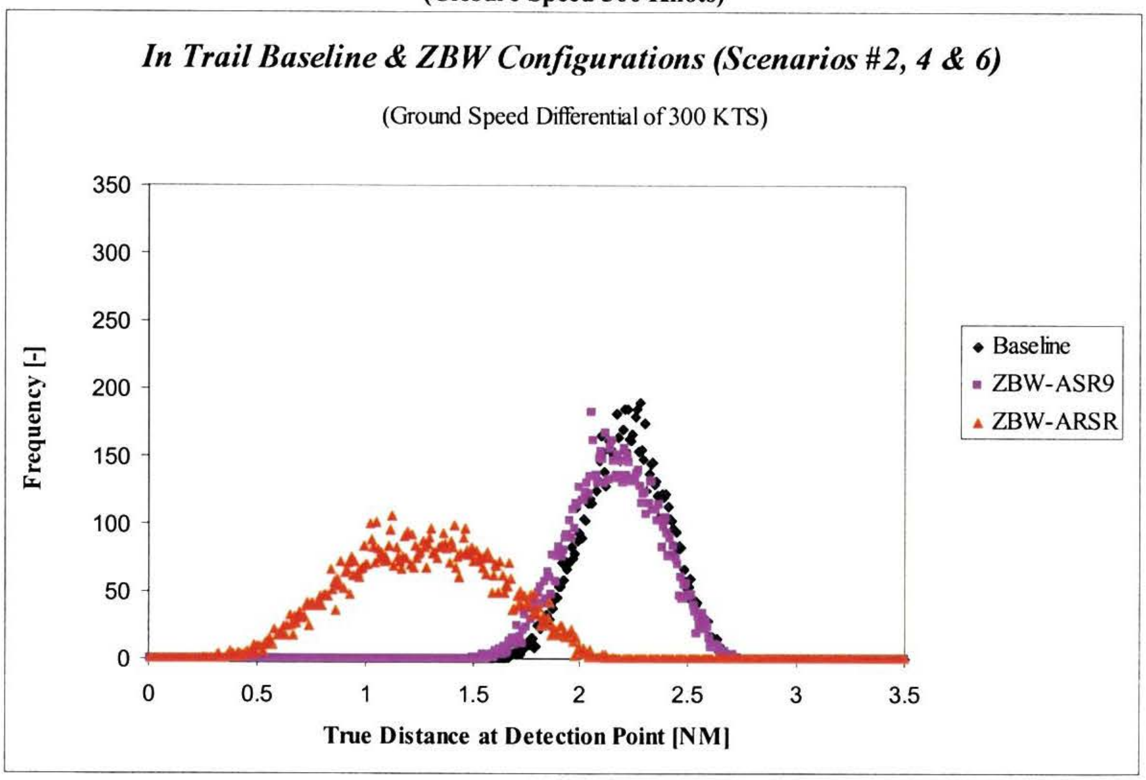

Figure 7: Histogram Plots of Actual In-trail Distances for Scenarios 2, 4, and 6

A comparison of Figures 6 and 7 shows a marked difference in actual distance of the aircraft depending on closure speed. This is, as one would expect, given that the faster aircraft covers more distance during each radar/processing system cycle. In addition, Figure 7 shows the ZBW-ARSR results to have greater variability at 300 Knots, as its histogram is more rounded than the peaked plots of the baseline and ZBW-ASR9.

3.2. Course Divergence Separation Data Analysis

Table 7 shows the six course divergence scenarios evaluated. Recall that the variable of interest in this analysis was the actual track of the aircraft at the instant when the "controller" first detects that the aircraft has turned 15±3.°

Scenario #	Radar System	Groundspeed (Knots)
7	Baseline	200±20
8	ZBW-ASR9	200±20
9	ZBW-ARSR	200±20
10	Baseline	400±20
11	ZBW-ASR9	400±20
12	ZBW-ARSR	400±20

Table 7: Course Divergence Separation Scenarios

Table 8 contains the statistical parameters associated with course divergence scenarios 7, 8, and 9, i.e., those conducted at 200 Knots. Figure 8 shows histogram plots of the results of the 10,000 ATPE runs for these course divergence scenarios conducted at 200 Knots.

Value	Scenario #7	Scenario #8	Scenario #9
Mean	107.5575	109.2817	129.629
Standard Error	0.030573	0.030821	0.062812
Median	107.5689	109.1575	129.5051
Standard Deviation	3.057287	3.082054	6.28122
Sample Variance	9.347001	9.499059	39.45372
Kurtosis	-0.45567	-0.48703	29.48704
Skewness	0.08549	0.164902	-1.18558
Range	16.67963	17.40209	30.1032
Minimum	99.99828	101.2688	117.7802
Maximum	116.6779	118.6709	147.8834
Sum	1075575	1092817	1296290
Count	10000	10000	10000
Confidence Level (95.0%)	0.059929	0.060414	0.123125

Table 8: Course Divergence Separation Scenarios Statistical Analysis (Groundspeed 200 Knots)

Table 8 shows that when the controller detects a track change of 15, ° the mean actual track change values for the baseline, ZBW-ASR9, and ZBW-ARSR systems were 32.6° (107.6 – 75), 34.3° (109.3 – 75), and 54.6° (129.6 – 75), respectively. Again, there is a close correlation between the systems (baseline and ZBW-ASR9) using the ASR-9 radar. However, the ZBW-ARSR system shows a much greater difference from the baseline system. This variance can be primarily attributed to the lower scan rate, higher latency time, and decreased display rate resident in the ZBW-ARSR system. Figure 8 also shows that the ZBW-ARSR system has greater variability than either the baseline or ZBW-ASR9. Both the baseline and ZBW-ASR9 histograms show distinct peaks around their means, whereas the ZBW-ARSR system has a more rounded plot around its mean.

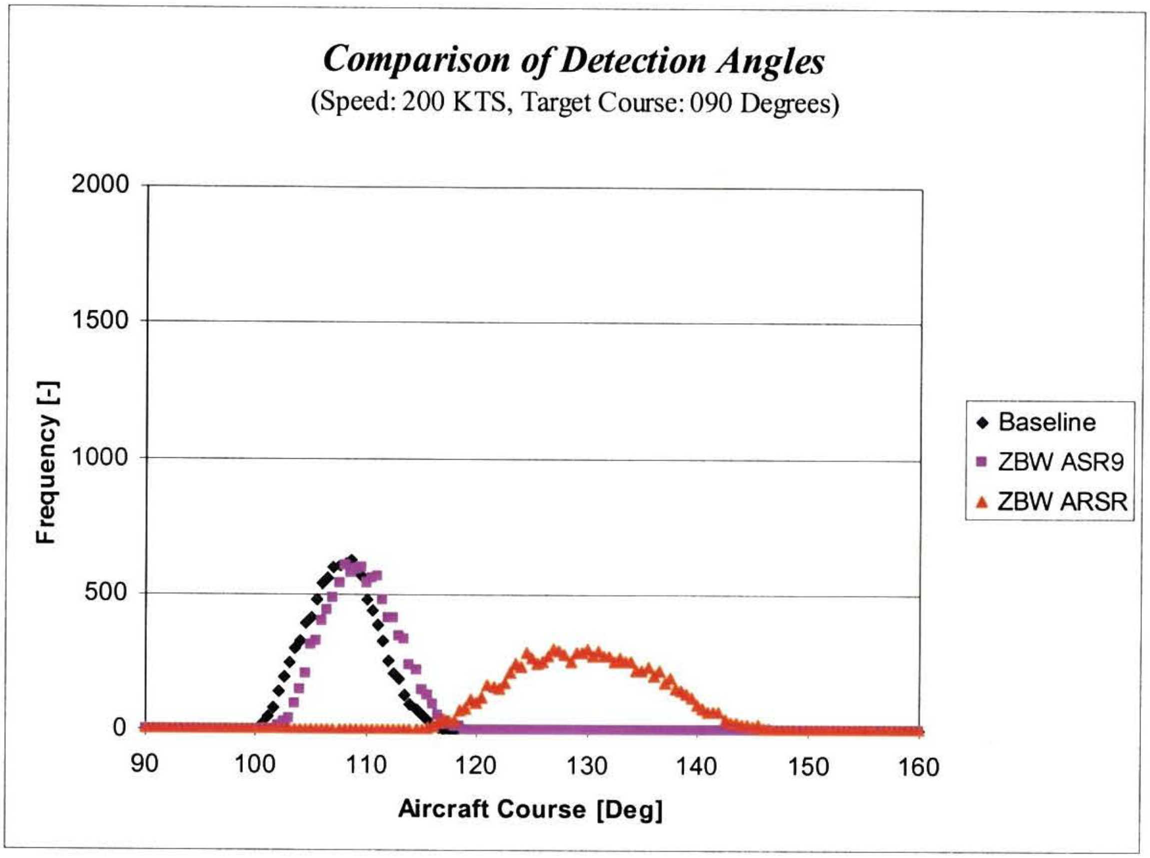

Figure 8: Histogram Plots of Actual Aircraft Course at Time of Detection for Scenarios 7, 8, and 9

Table 8 contains the statistical parameters associated with course divergence scenarios 10, 11, and 12, i.e., those conducted at 400 Knots. Figure 9 shows histogram plots of the results of the 10,000 ATPE runs for these course divergence scenarios conducted at 400 Knots.

Value	Scenario 10	Scenario 11	Scenario 12
Mean	98.74829	99.62878	109.7631
Standard Error	0.014541	0.014451	0.028945
Median	98.75649	99.64402	109.7321
Standard Deviation	1.454123	1.445075	2.894493
Sample Variance	2.114475	2.088241	8.378088
Kurtosis	-0.50577	-0.68184	-0.75029
Skewness	0.03607	-0.00144	0.029887
Range	7.632817	7.831245	14.59849
Minimum	95.04909	95.8857	102.7513
Maximum	102.6819	103.7169	117.3498
Sum	987482.9	996287.8	1097631
Count	10000	10000	10000
Confidence Level (95.0%)	0.028504	0.028326	0.056738

Table 9: Course Divergence Separation Scenarios Statistical Analysis (Groundspeed 400 Knots)

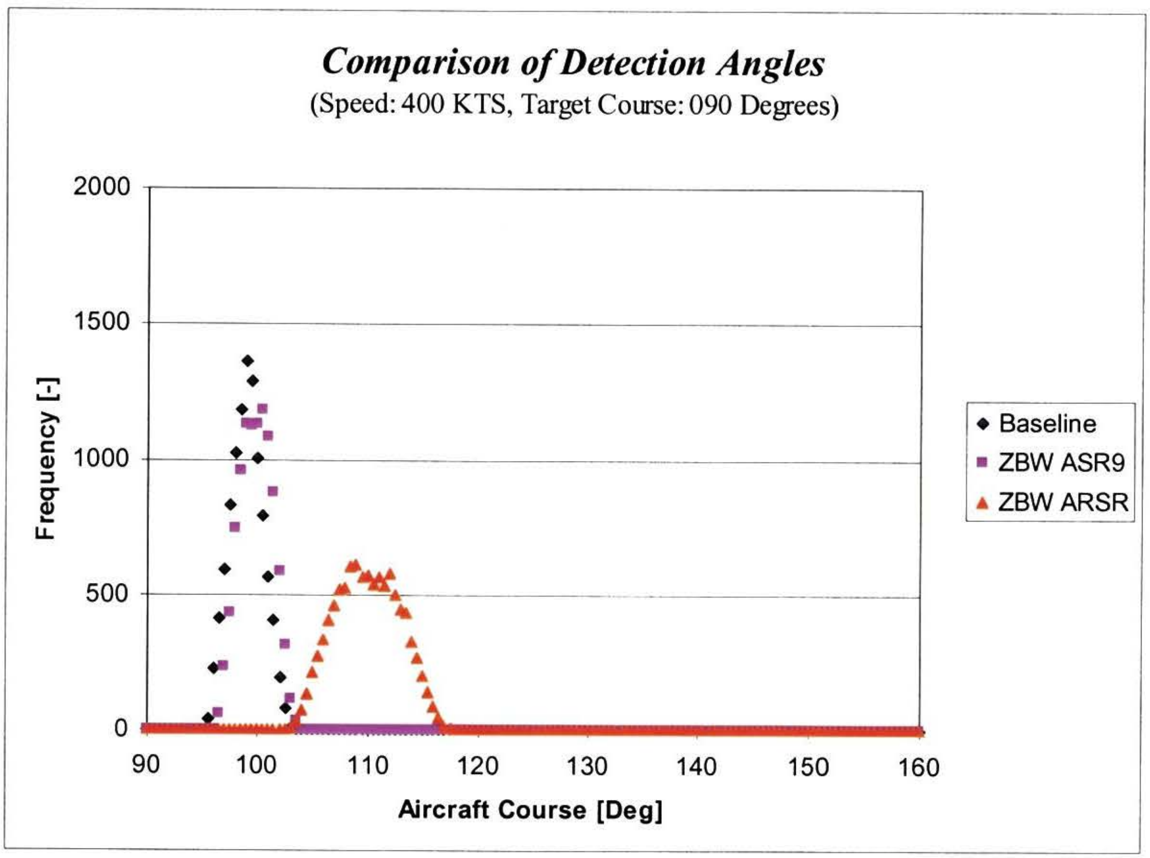

Figure 9: Histogram Plots of Actual Aircraft Course at Time of Detection for Scenarios 10, 11, and 12

For the 400 Knots scenarios, Table 9 shows that when the controller detects a track change of 15, ° the mean actual track change values for the baseline, ZBW-ASR9, and ZBW-ARSR systems were 23.7° (98.7-75), 24.6° (99.6-75), and 34.8° (109.8-75), respectively. Again, there is a close correlation between the systems (baseline and ZBW-ASR9) using the ASR-9 radar. However, the ZBW-ARSR system shows a much greater difference from the baseline system. This variance can be primarily attributed to the lower scan rate, higher latency time, and decreased display rate resident in the ZBW-ARSR system. A comparison of Tables 8 and 9, show lower values for actual aircraft course at time of detection for the 400 Knots case versus the 200 Knots case. This is because the slower aircraft actually has a higher turn rate (approximately 2°/second at 200 Knots) than the faster aircraft (approximately 1°/second at 400 Knots). Thus, the slower aircraft makes a greater turn than the faster aircraft during the course of a radar update cycle.

Figure 9 also shows that the ZBW-ARSR system has greater variability than either the baseline or ZBW-ASR9. Both the baseline and ZBW-ASR9 histograms show distinct peaks around their means, whereas the ZBW-ARSR system has a more rounded plot around its mean.

4.0. Results and Conclusions

1. As previously stated, the goal of the in-trail separation study was to determine what the adjustments to application of displayed separation criteria should be on a ZBW system using either ASR-9 or ARSR radars in order to ensure that the actual aircraft to aircraft separation is not less than that achieved using the baseline system. The results are derived using a 2σ (or approximately 95%) analysis of the statistical data presented in paragraph 3.1. In other words, adjustments in the application of separation for ZBW-ASR9 and ZBW-ARSR systems will ensure that for approximately 95% of the evaluated cases, the actual in-trail distance between aircraft will not be smaller than the actual distance between aircraft when using a baseline system.

These results are summarized in Table 10. The mean + 2σ values for each in-trail scenario are computed and shown as D in Table 10. The D values for ZBW-ASR9 and ZBW-ARSR are subtracted from the baseline D to obtain an adjustment in the application of separation for each radar system at the closing speeds of 150 Knots and 300 Knots.

Variable \ Scenario	Baseline (#1)	ZBW-ASR9 (#2)	ZBW-ARSR (#3)	Baseline (#4)	ZBW-ASR9 (#5)	ZBW-ARSR (#6)
	Closing at 150 Knots			Closing at 300 Knots		
Mean [NM]	2.60	2.58	2.13	2.20	2.15	1.25
SD (σ) [NM]	0.12	0.13	0.20	0.19	0.21	0.34
2σ [NM]	0.24	0.26	0.40	0.37	0.41	0.69
D [NM]	2.36	2.32	1.73	1.83	1.74	0.57
Separation Adjustment [NM]		**-0.04**	**-0.64**		**-0.09**	**-1.26**

Table 10: Actual In-trail Separation Values (2σ analyses)

2. Based on Table 10, the following conclusions can be drawn concerning the application of in-trail separation standards:

a. when using ASR-9 radar data in the ARTCC HCS/DSR processing/display system with a 6 second write rate, no adjustment is necessary in the application of separation minima.

b. when using ARSR radar data in the ARTCC HCS/DSR processing/display system and closure speeds exceed approximately 120 Knots adjustments to the application of in-trail separation as shown in Table 11 should made.

Closure Speed (Knots)	In-trail Separation Application Adjustment (NM)
120	+0.5
150	+0.6
180	+0.75
210	+0.9
240	+1.0
270	+1.15
300	+1.25

Table 11: In-trail Separation Application Adjustments Using ARSR

3. As previously stated, the goal of the course divergence separation study was to determine what the displayed course divergence should be on a ZBW system using either ASR-9 or ARSR radars in order to ensure the same relative course divergence afforded by the baseline system. The results are derived using a 2σ (or approximately 95%) analysis of the statistical data presented in paragraph 3.2. In other words, angular adjustments for ZBW-ASR9 and ZBW-ARSR systems will ensure that for approximately

95% of the evaluated cases, the actual course divergence between aircraft will not be smaller than the actual course divergence between aircraft when using a baseline system.

These results are summarized in Table 12. The mean + 2σ values for each course divergence scenario are computed and shown as D in Table 12. The D values for ZBW-ASR9 and ZBW-ARSR are subtracted from the baseline D to obtain a course divergence adjustment for each radar system at the true airspeeds (TAS) of 200 Knots and 400 Knots.

Scenario / Variable	Baseline (#7)	ZBW-ASR9 (#8)	ZBW-ARSR (#9)	Baseline (#10)	ZBW-ASR9 (#11)	ZBW-ARSR (#12)
	200 Knots TAS			400 Knots TAS		
Mean [Deg.]	107.56	109.28	129.63	98.75	99.63	109.76
SD (σ) [Deg.]	3.06	3.08	6.28	1.45	1.45	2.89
2σ [Deg.]	6.11	6.16	12.56	2.91	2.89	5.79
D [Deg.]	113.67	115.45	142.19	101.66	102.52	115.55
Delta [Deg]		**1.78**	**28.52**		**0.86**	**13.89**

Table 12: Actual Course Divergence Values (2σ analyses)

4. Based on Table 12, the following conclusions can be drawn concerning course divergence separation standards:

a. when using ASR-9 radar data in the ARTCC HCS/DSR processing/display system modified to write at 6-second intervals, relatively small course divergence angular adjustments are necessary. These adjustments range from 1.78° at 200 Knots groundspeed to 0.86° at 400 Knots.

b. when using ARSR radar data in the ARTCC HCS/DSR processing/display system a course divergence angular adjustment is necessary. This adjustment ranges from 28.52° for an aircraft at 200 Knots groundspeed to 13.89° for an aircraft at 400 Knots groundspeed. Thus for either aircraft at 200 Knots groundspeed in a course divergence separation scenario, a course divergence angle of 43.52° (original 15° + 28.52° adjustment) would have to be observed and maintained for vertical separation to be discontinued.

c. since this study does not address radar system position errors caused by system plane projections between aircraft broadcasting mode C information and non-mode C aircraft, the course divergence procedures can only be applied between validated mode C aircraft.

d. altitude limitation for this study is bounded by the slant range distance of 40 NM for non-mode C aircraft. Basic altitude restrictions are those of each individual sensor or 41,000 ft Mean Sea Level (MSL) whichever is greater.

(Note: It must be emphasized that the results reported in this study are heavily dependent upon the DSR display rates as shown in Table 3. In particular, there is some concern as to whether the ZBW-ASR9 system can achieve a 6 second DSR display rate. If this is the case, the results presented above for the ZBW-ASR9 would be closer to those reported for the ZBW-ARSR.)

5.0. References

1. FAA Order 7110.65P, Air Traffic Control, 2/19/2004.

2. Sensor Performance Specifications, undated, FAA.

3. Willems, Ben (Engineering Research Psychologist, William J. Hughes Technical Center), "Deviation and Recognition" Email, 10/15/2004.